

Numerical Simulation and the challenges of turbulent flows at the DLR Institute of Aerodynamics and Flow Technology Braunschweig / Göttingen

Knowledge for Tomorrow

Site Locations

Braunschweig: ~ 160 Employees



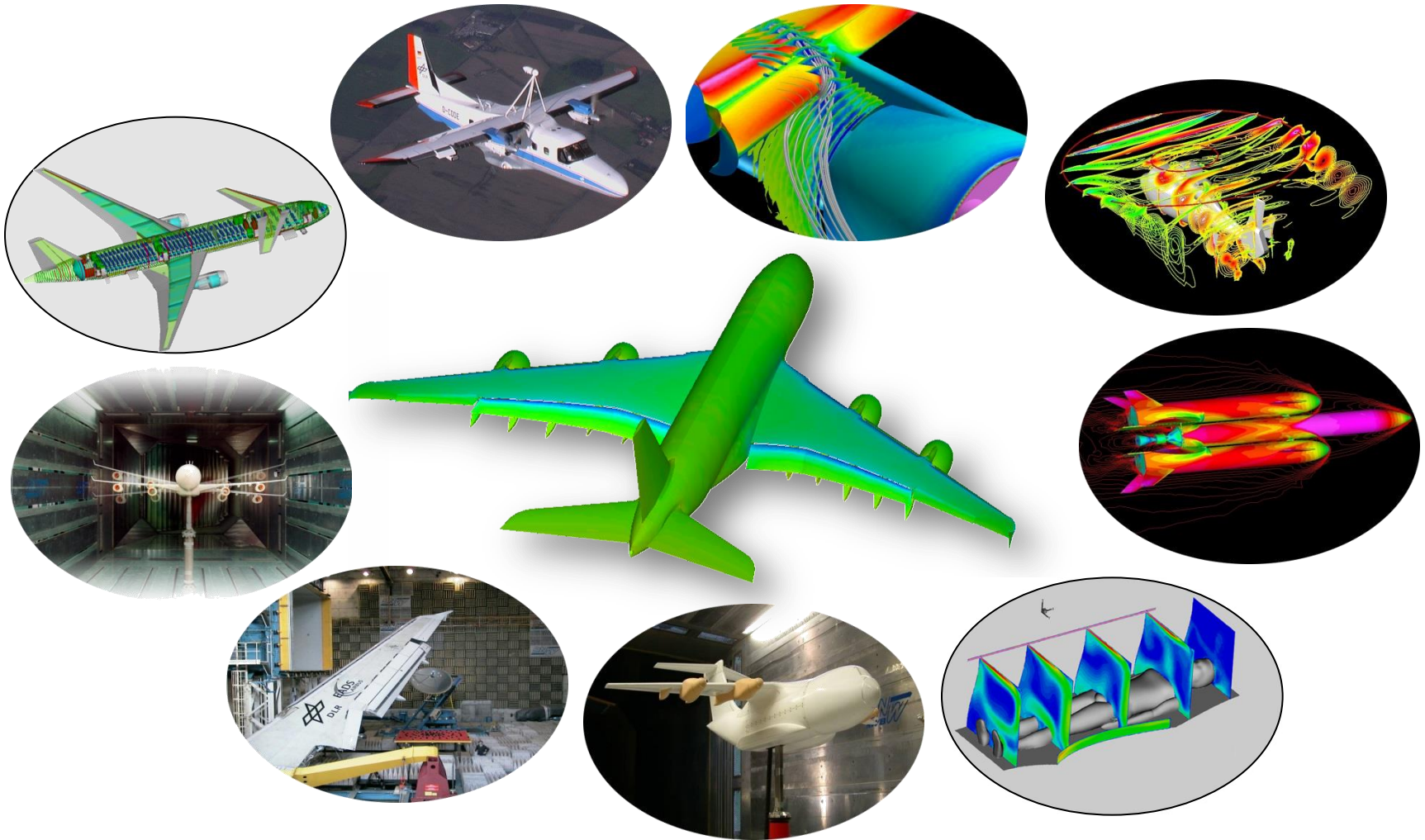
Göttingen / Köln: ~ 160 Employees



~ 320 Employees



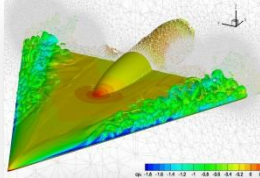
Our Research Areas



Covering the complete regime of flow speeds



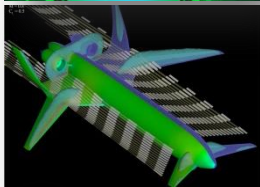
Scientific Core Competencies



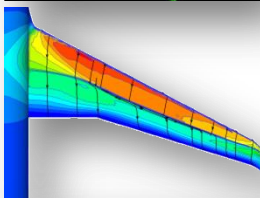
Multidisciplinary Numerical Simulation and Optimization
-> C²A²S²E



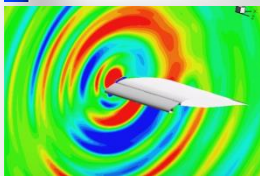
Measurement Technologies and Experimental Validation



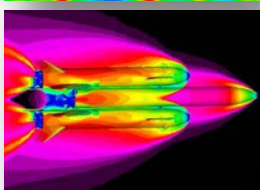
Conceptual Design and Configuration Analysis



Aerodynamic Design and Analysis



Aeroacoustic Prediction and Noise Reduction



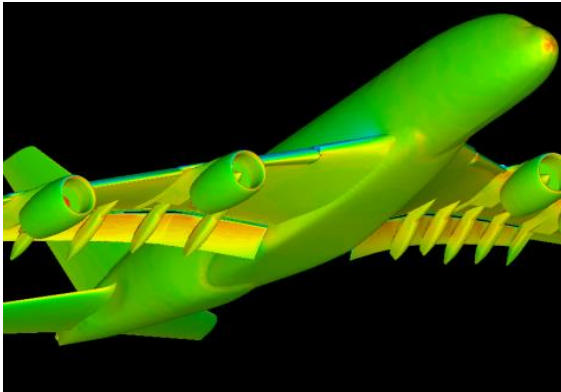
Aerothermodynamic Design and Analysis



Flow Technology

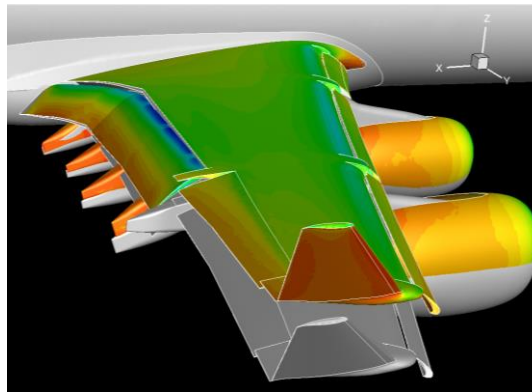
Multidisciplinary Numerical Simulation and Optimization

Main Focus



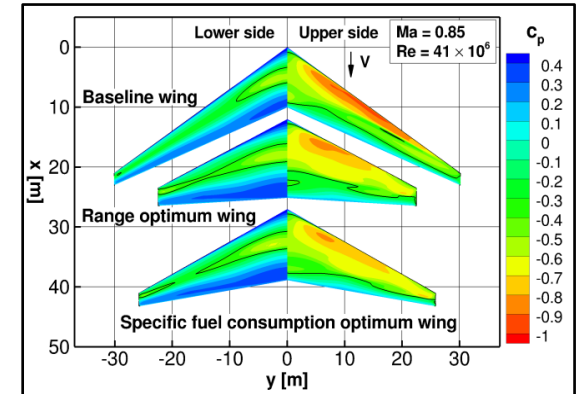
- **The product is the (virtual) aircraft**
- Shape optimization
- Multi-disciplinary simulation
- Multi-disciplinary optimization
- Quantification of aerodynamic uncertainties
- Simulation based certification

Technologies & Methods



- CFD-Tools (TAU, FLOWer)
- Physical Modeling
- Adjoint methods for sensitivities
- Coupling of disciplines
- Surrogates, ROMs
- HPC

Application



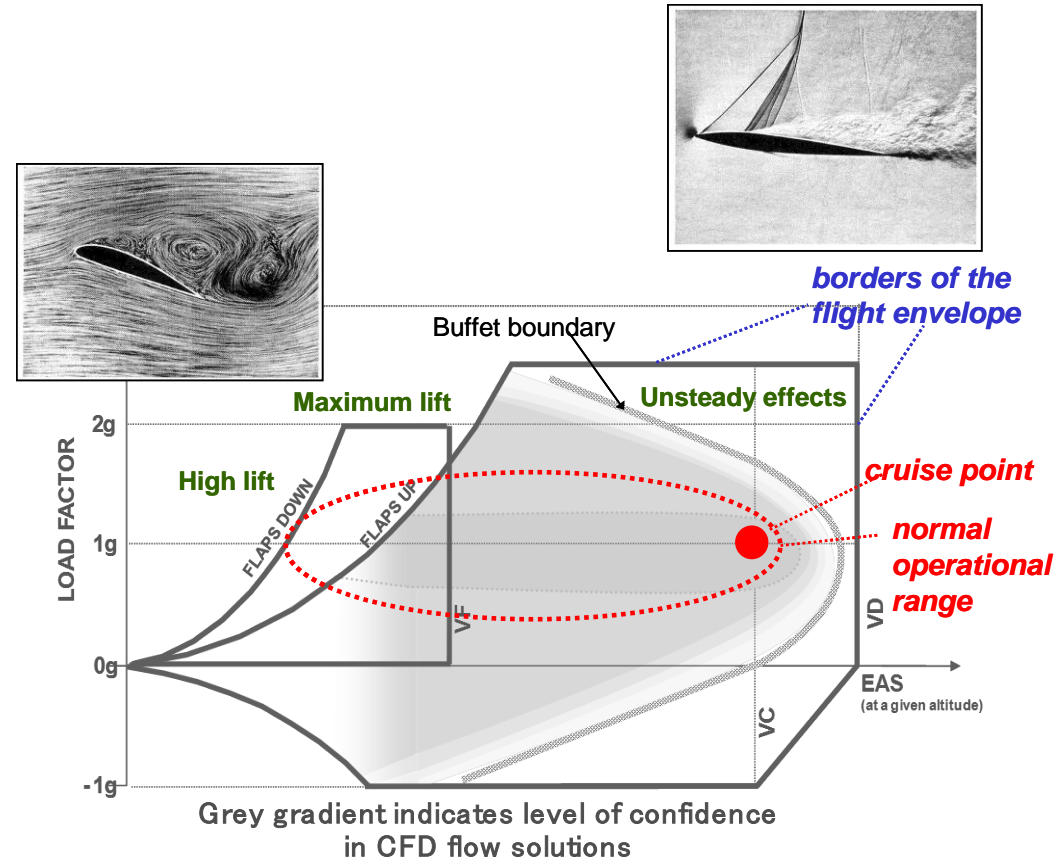
- Maneuver & gust simulations
- Prediction of aerodynamic data for performance, loads and S&C
- Design of aircraft components, trade studies
- Optimization of full aircraft configuration



Multidisciplinary Numerical Simulation and Optimization Towards Virtual Aircraft Design and Flight Testing

Challenges

- Full flight envelope
- Coupling of Disciplines
- Large Scale Computations
- Reduced Order Modeling
- Multi-Disciplinary Analysis & Optimization



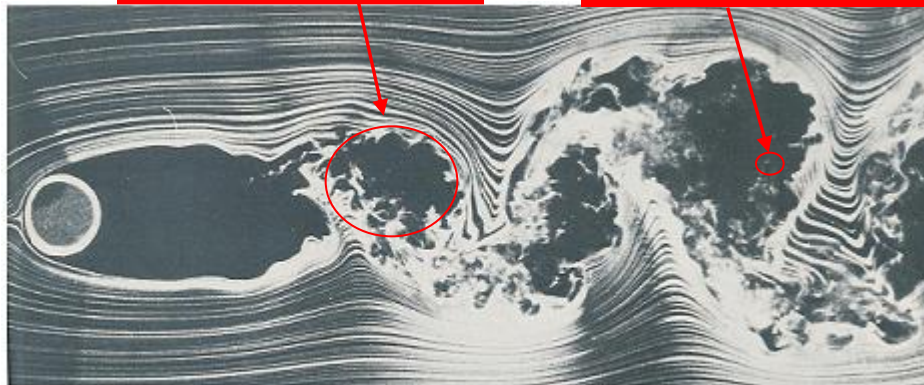
Linked to DLR Guiding Concept: Virtual Aircraft

Challenges of turbulent flows

- Size of the **large scale vortices** determined by the **size of the body** l_0
 - Large-scale vortices are insensitive to Reynolds number
- Size of the **smallest vortices** depends on the **Reynolds number**
 - Smallest scales become smaller as Reynolds number increases
 - Smallest vortices are dissipated into heat
 - Size of smallest persistent vortices is given by the so-called Kolmogorow scale η
- Ratio of smallest scales to largest scales $\eta/l_0 \sim \text{Re}^{-3/4}$

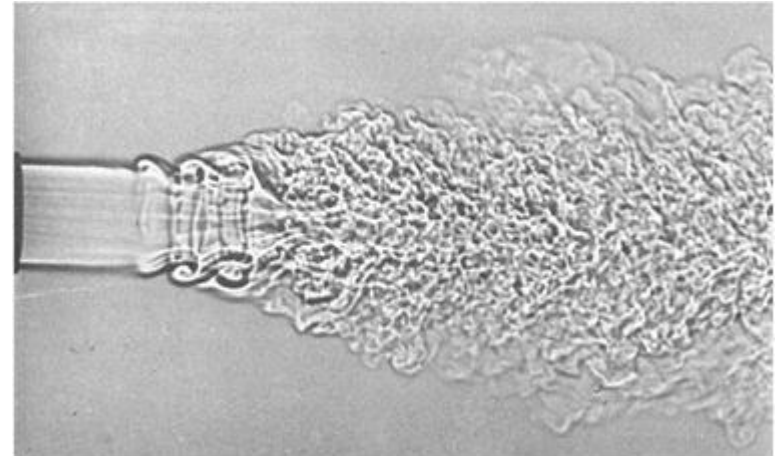
Largest vortices $\sim l_0$

Smallest vortices $\sim O(\eta)$



(a) Visualizing turbulent cylinder wake at $\text{Re} = 10000$

[Courtesy: Thomas Corke and Hassan Nagib; from *An Album of Fluid Motion* by van Dyke (1982)]



Scales of turbulent flows in aerospace aerodynamics

- Large range of scales (vortices/eddies of different sizes) in turbulent flows
 - Size of largest vortices = characteristic size l_0 of the geometry: of the order of 10m
- Size of smallest vortices
 - very small due to the large Reynolds number
 - even much smaller in the near-wall region of the boundary layers adjacent to solid surfaces

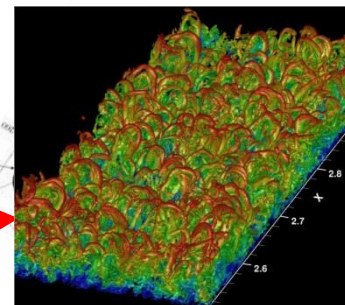
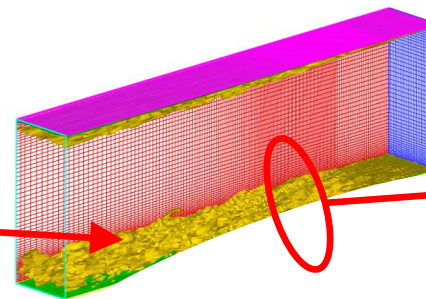
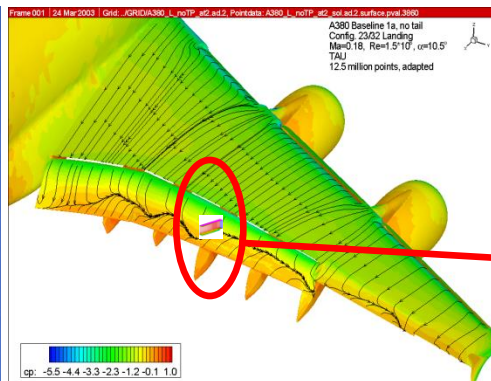
Large-scale vortices
(Wake vortices):
Characteristic vortex
size given by the
macroscopic length
scale of airplane
elements (e.g. wing)

$$\eta/l_0 \sim Re^{-3/4}$$

Vortices of separated
boundary layer flow:
Size of separation region is
given by dimension e.g. of
the flap (flap chord)

Vortices in outer
part of the turbulent
boundary layer:
Weak Re-dependence

Smallest structures:
Koherent structures
in the near-wall
region
(Hairpin vortices)
Large Re-
dependence



Turbulence modelling versus turbulence resolving methods

← **RANS** →

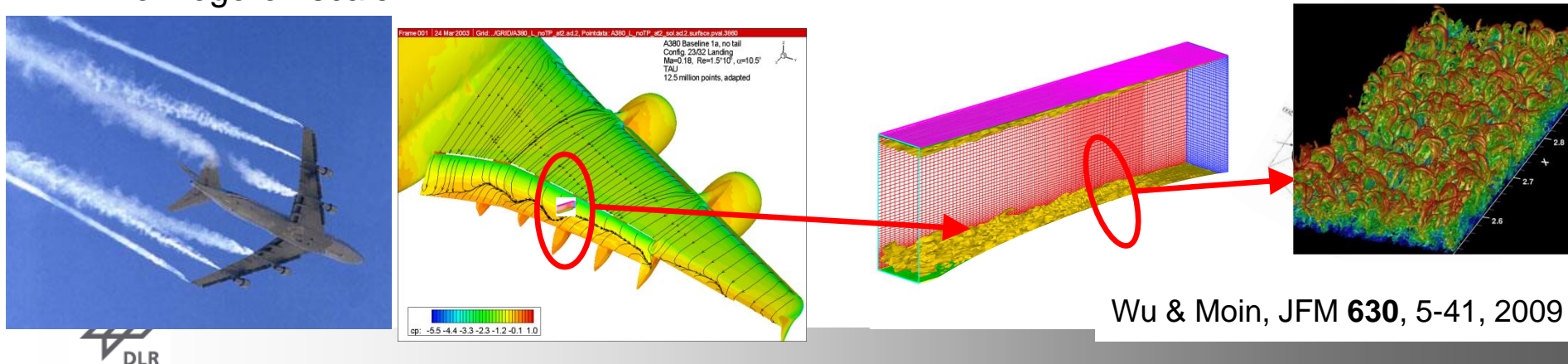
➤ Statistical turbulence modelling approaches

- Reynolds-**A**veraged **N**avier-**S**tokes equations (**RANS**)
- Resolve macroscopic vortices
- Model the effects of the small-scale turbulence on the large-scale fluid motion

← **LES** **DNS** →

➤ Turbulence-resolving approaches

- **D**irect **N**umerical **S**imulation (**DNS**): resolve down to the Kolmogorov-scale
- **L**arge-**E**ddy **S**imulation (**LES**): Resolve down to hairpin vortices, but not down to Kolmogorov-scale

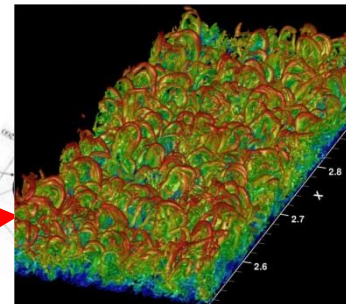
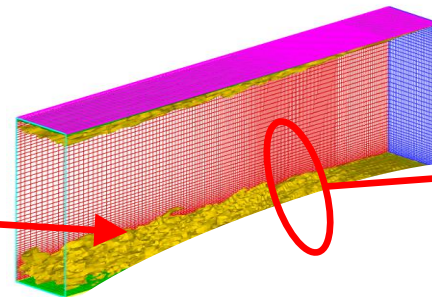
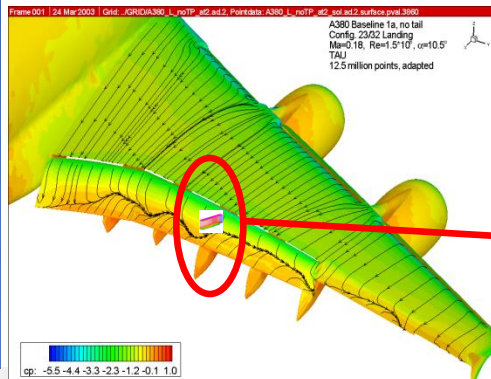
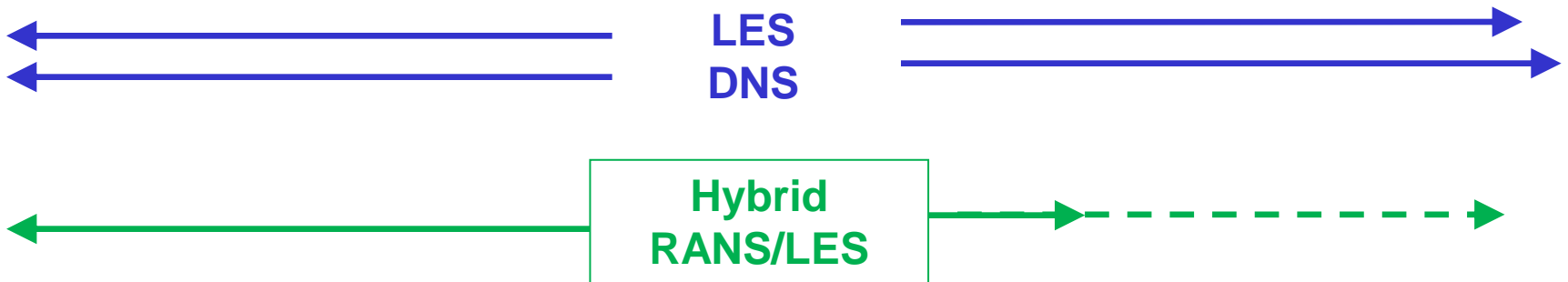


Turbulence modelling versus turbulence resolving methods

← **RANS** →

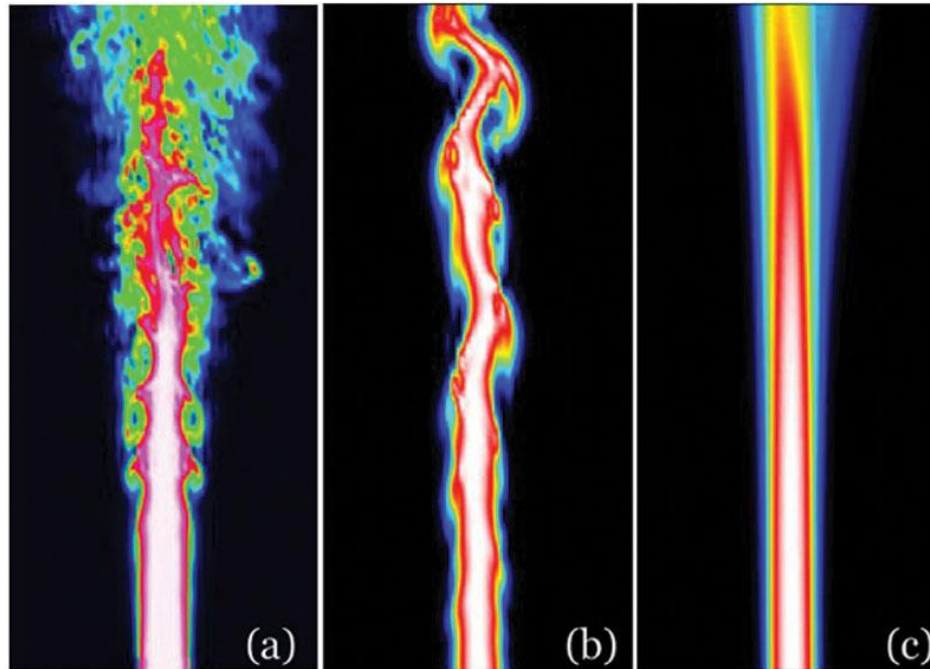
➤ Statistical turbulence modelling approaches

- Reynolds-Averaged Navier-Stokes equations (**RANS**)
- Resolve macroscopic vortices
- Model the effects of the small-scale turbulence on the large-scale fluid motion



Wu & Moin, JFM **630**, 5-41, 2009

Comparison DNS – LES – RANS



Givi et al.
Carnegie-
Mellon Univ.,
Pittsburgh,
PSC annual
report 2009

**Direct numerical
simulation (DNS):**
resolve irregular
vortical motion
down to
the smallest
persistent eddies

**Large-Eddy
simulation (LES):**
resolve irregular
vortical motion of
the large-scale
energy-containing
vortices.
Model effects of
the smallest eddies

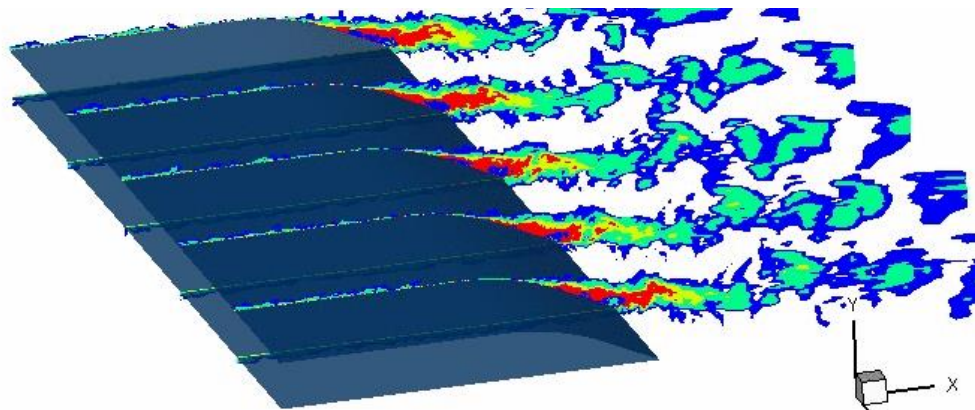
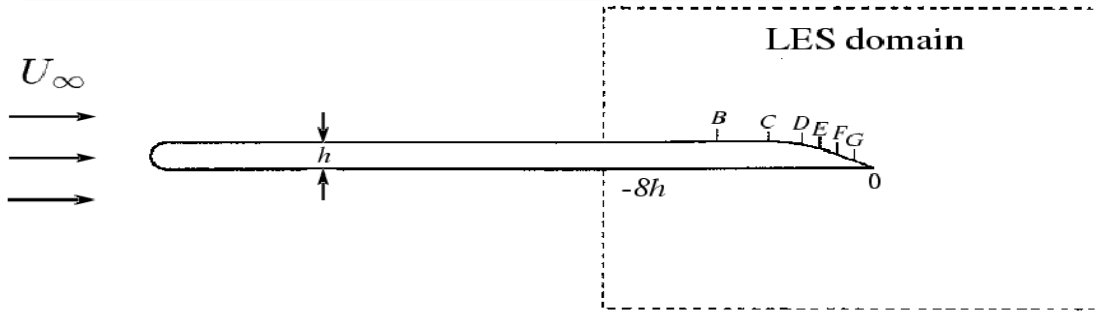
**Reynolds averaged Simulation
(RANS):**

- Approximate the statistically averaged (sometimes: time-averaged) solution of DNS (or LES)
- Model the effects of the irregular vortices on the mean flow

DNS/LES versus RANS

Direct Numerical Simulation (DNS) and Large eddy simulation (LES):

- Separation line is 3D and changing with time
- Unsteady vortex shedding downstream of the separation point
- Requires an unsteady 3D simulation

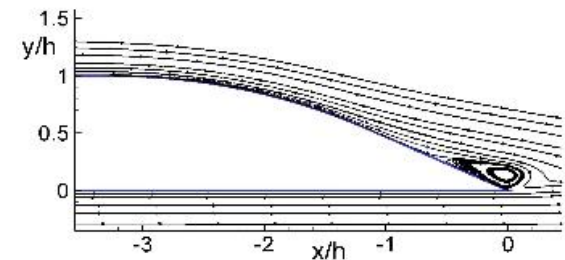


Reynolds averaged simulation (RANS):

- 2D simulation possible
- Steady state solution
- Steady state recirculation region at the trailing edge

RANS solution

- approximates a statistically averaged flow solution
- Figure below: mean streamlines



Motivation: Digital aerospace products

Goal: CFD as a tool for future aircraft

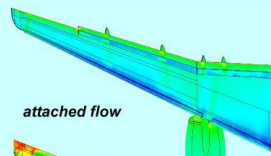
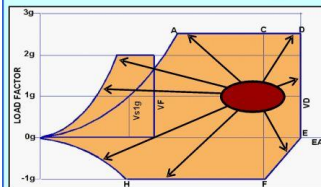
- design
- optimization
- certification

Challenges

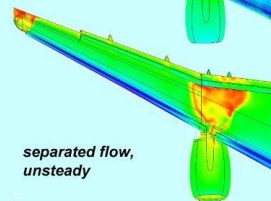
- A/δ_{99} extremely large: large Re and large A
=> Extremely large cost of a single LES
- Huge number of simulations (10^5 to 2×10^7) required for design and optimization of a new aircraft
=> RANS only affordable high fidelity approach



Full flight envelope coverage: *CFD mostly done near cruise point*



attached flow



separated flow, unsteady

configurations:

clean



airbrakes deployed



high lift



- 50 flight points
- 100 mass cases
- 10 a/c configurations
- 5 maneuvers
- 20 gusts (gradient lengths)
- 4 control laws

~ 20,000,000 simulations

Engineering experience for **current** configurations and technologies

~ 100,000 simulations



CFD Solver TAU

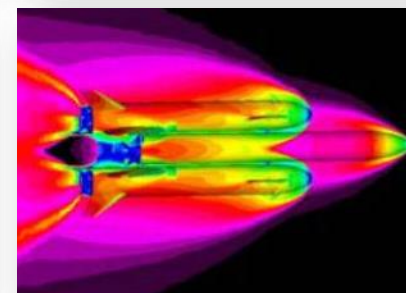
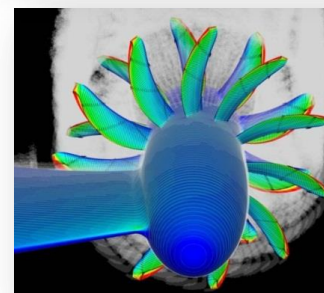
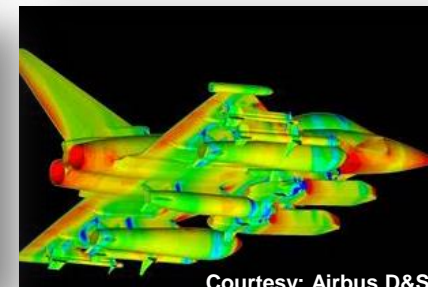
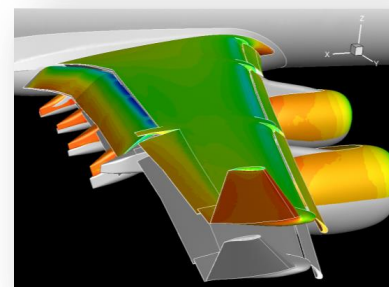
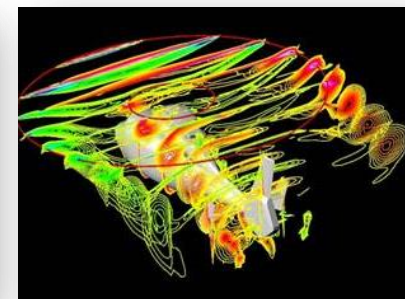
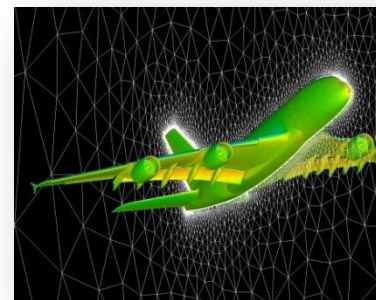
Turbulence +
Transition

CFD-
Algorithms

Technology
Integration

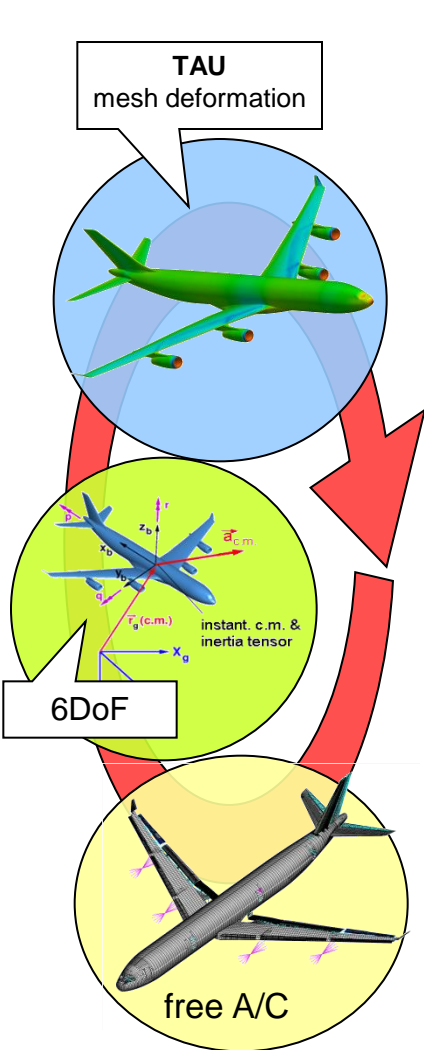
Reynolds-averaged Navier Stokes Code

- Unstructured, overlapping grids, adaptation
 - Finite Volume method 2nd order
 - Advanced turbulence models, e.g. RSM
 - Hybrid RANS/LES
 - Linear, adjoint solver
 - Interfaces for multidisciplinary coupling, e.g. FlowSimulator
 - Continuous verification & validation efforts
-
- Applied in European aircraft industry, e.g. Airbus, Airbus D&S, Airbus Helicopter, RRD, ...)
 - Research platform for European universities and research organizations

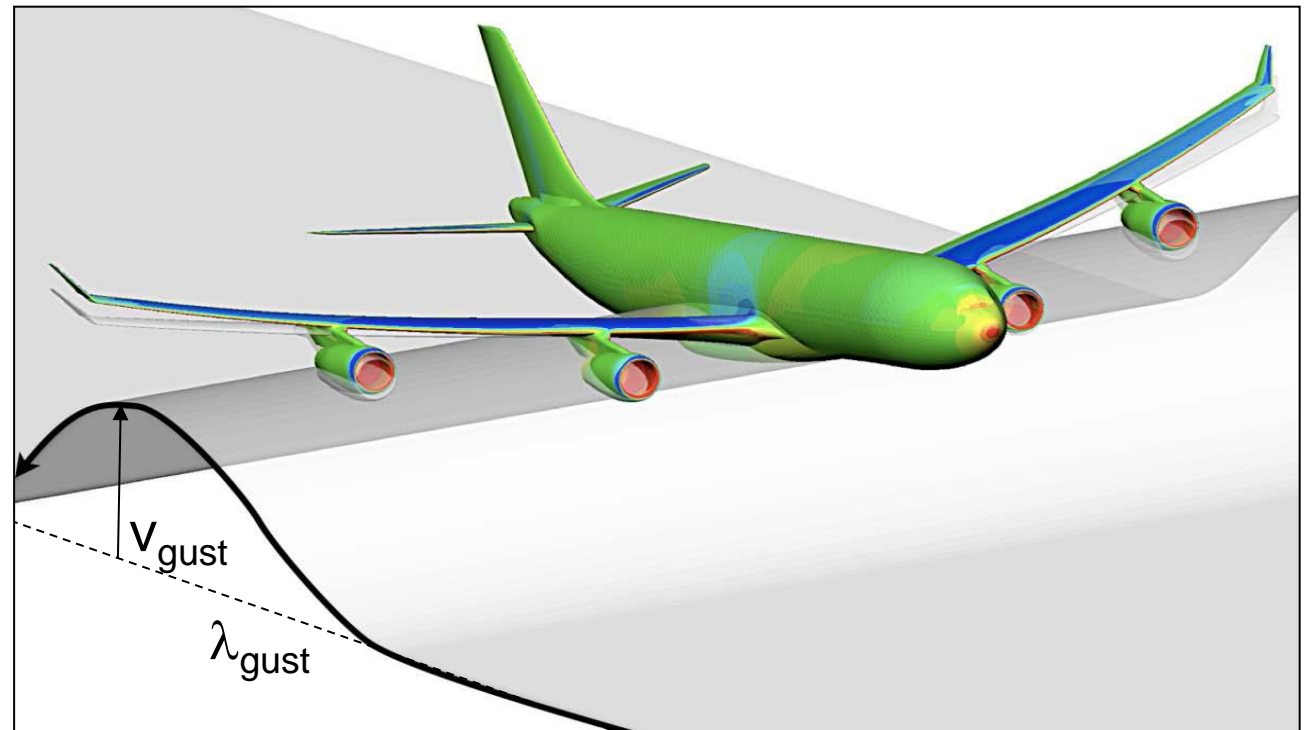


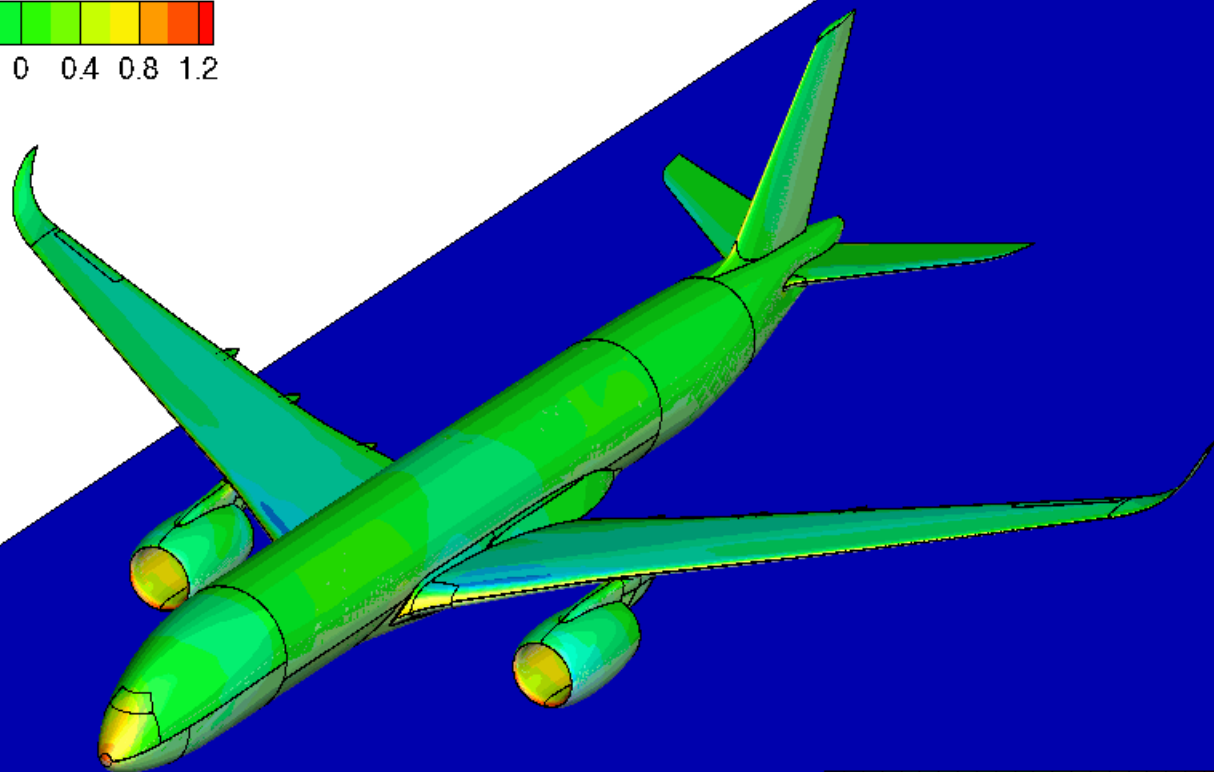
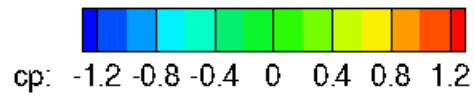
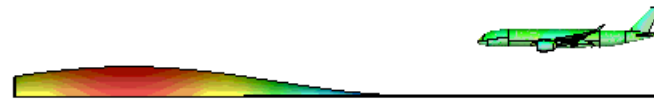
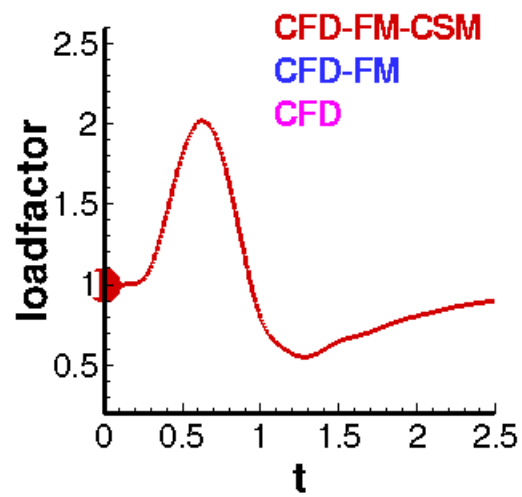
Maneuver Simulation

Gust encounter of Transport Aircraft under Cruise Conditions



- Gust modeling via
 - Disturbance velocity approach
 - Resolved gust approach
 - Interface to arbitrary gust shapes (PALM)
 - Coupling with high-order code FLOWer4





Maneuver Simulation

Gust encounter of Transport Aircraft under Cruise Conditions

Conditions

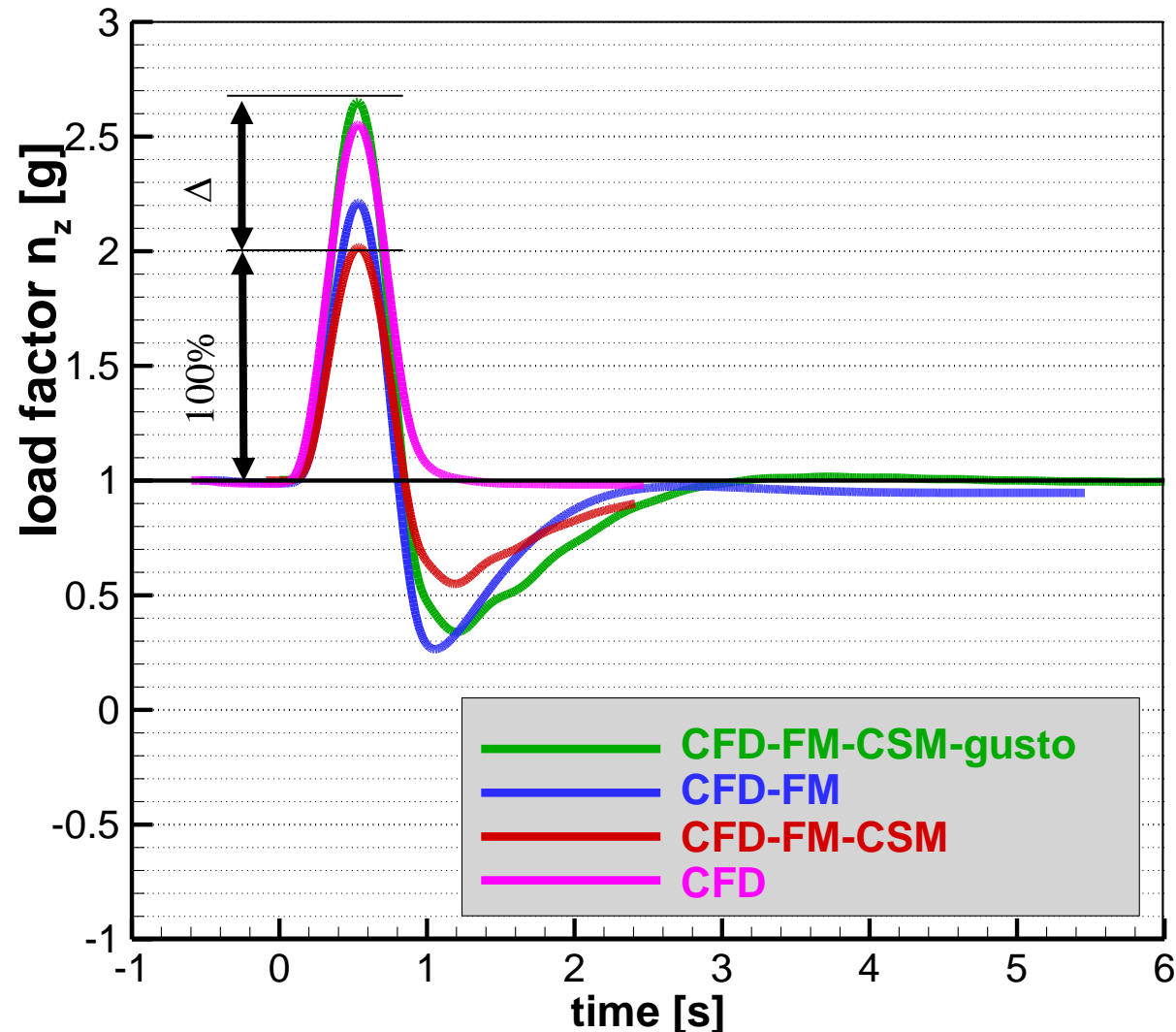
- $M = 0.836$
- $m = 150 \text{ to}$
- $Re = 77 \times 10^6$
- $H = 8.2 \text{ km}$
- $\lambda_{\text{gust}} = 213.36$
- $v_{\text{gust}} = 10.52 \text{ m}$

Comparison

- CFD-FM-CSM
- CFD-FM
- CFD
- Airbus approach gusto

Outlook

- Prediction of effectiveness of load alleviation systems



Summary

- Numerical Simulation
 - Key enabler for future aircraft design
 - Potential not yet fully exploited - **Digital Aircraft / Digital Product**

